Transcript invited review

Convective and non-convective mixing in AGB stars

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Slide 1 (Title slide)

Hello everybody – unfortunately and regretfully I cannot be here today, but fortunately John has agreed to present my **talk about convective and non-convective mixing**. As you all know - and as John has probably reconfirmed this morning – our understanding of the physics of mixing in stellar evolution in general, and this includes of course AGB stars in particular, is not exactly in a satisfying state. While we do get some global properties maybe right the list of things that we cannot reproduce in our models accurately, is getting longer as observations are getting better, more accurate and more detailed. It has been said that stellar evolution is one of the most successful theories in astronomy. This maybe a somewhat star-centric view (there is nothing wrong about that!), but I think everyone agrees – it has a glorious past. However, modern observations require much more in terms of accuracy and detail, and the lack thereof is severely inhibiting the usefulness of this field for helping to address some of the more general questions in astronomy, for example in the emerging field of near-field cosmology. With better simulations we could use detailed abundance observations to precisely characterize extra-galactic populations. Thus there is a real need for improving significantly in the near future.

Having made these introductory remarks – I will try to strike a balance between pointing out things that are not so well known

and how to maybe fix them, and reporting on what may be some real progress.

Slide 2 (Variation of mixing length parameter)

Let's start with the convective envelope. Most stellar evolution calculations use the MLT with a constant mixing length parameter calibrated by using a solar model. However, we know for certain that the notion of a constant mixing length parameter throughout all phases and conditions in stellar evolution – as if this were a natural constant – is plain wrong. This figure is from a very important paper by Ludwig, Freytag and Steffen (1999). They have determined the mixing-length parameter from their set of 2D radiation hydrodynamic simulations of the outer convection layer in stars similar to the sun. Isolines connect the same α_{MLT}. These simulations show that α_{MLT} is very sensitive to the temperature (and thus to the depth of the convection zone), and that just within the small parameter range covered here, say within +-1000K the α_{MLT} parameter changes by of the order +-15%. If – and John Lattanzio would confirm that, wouldn't I? – we change α_{MLT} in this range for AGB simulations many important features change quantitatively, most notably dredge-up. This is known since first shown by Boothroyd and Sackmann (1988), and it makes in fact the lengthy discussion about dredge-up efficiency a couple of years ago partly obsolete. Hot-bottom burning is also very sensitive to α_{MLT}, and this is in particular true for super-AGB stars and massive low-metallicity AGB stars.

Slide 3 (AGB envelope hydro simulations)

So, what can be done? Mazzitelli, D'Antona and Ventura have for many years now promoted and studied the Full-spectrum turbulence convection model. It overcomes one important simplification of MLT: convection does not only consist of one blob size, but there is a spectrum of scales. I think this is a step

in the right direction. Unfortunately, so far it seems that no really convincing validation case for AGB envelope convection has been identified. This is because other uncertain input physics, like mass loss, other sources of mixing (rotation and gravity waves, we will get to that!) and in some cases nuclear reaction rates, have a similar, independent effect on the same astrophysical observable, e.g. certain abundances, like the $^{12}C/^{13}C$ ratio. Therefore, validating a convection model with astrophysical observations may be a difficult, because degenerate problem.

Then, one is left with simulations. The two figures on this slide show 3D hydrodynamic convection simulations of AGB envelopes. The figure left from a simulation by Freytag shows vorticity, and one can indeed see structures on a range of scales. However, 4 or 5 large-scale systems dominate the convective velocities. On the right we see a snapshot of the temperature fluctuations of a simulation by Porter and Woodward. In their simulations the dominating largest scale was a global dipolar mode. According to the authors of these two studies the difference is caused by the assumptions made on the inner boundary conditions. In this context it is interesting to note that the fully convective C-burning core convection simulations of the immediate SNIa progenitor evolution by Kuhlen etal (2005) show a similar dominating dipolar mode as the Porter and Woodward AGB envelope simulations. It would be interesting in its on right to study the hydrodynamic properties of fully convective gaseous spheres.

Porter and Woodward have derived – as did Ludwig etal 1999 for their 2D RHD models – a mixing-length parameter of $\alpha_{MLT} \sim$ 2.6. These simulations, both by Freytag and by P&W did not resolve the inner parts of the envelope convection, which is so crucial for nucleosynthesis. An estimate of the computational cost for sufficiently resolved simulations encountering the entire convective envelope, taking into account advances in code

efficiency, better grid topologies, computational speed, new supercomputing platforms etc. leads to the conclusion that it will be technically possible to address the problems in AGB envelope convection, including the effects at the bottom of the convective envelope, computationally by the end of the decade. This is of course assuming that the effort is made.

Slide 4 (Multi-D HD simulations of He-shell flash convection - motivation)

I will now move on to the multi-dimensional He-shell flash convection simulations we have performed at Los Alamos over the past two years. When we started this project we had a number of goals in mind. First of all, the hydrodynamics of He-shell flash convection has never been simulated before in any detail. So, we wanted to investigate the hydrodynamical properties, and the topology of He-shell flash convection. For example, how well does MLT describe the vertical velocity profile of the convection zone? What are the dominating scales? What is the dependence on resolution, and on the nuclear energy generation? Obtaining a resolved velocity distribution from hydrodynamic simulations can give a new framework to study short-lived, T-dependent s-process branching fueled by the ^{22}Ne neutron source. And, most importantly, we wanted to study convection induced mixing across the convective boundaries. From several 1D stellar evolution studies using a parameterized recipe for convective overshooting (e.g. Herwig 2000, Lugaro etal. 2003) we know that overshooting at the bottom of the He-shell flash convection zone can have important effects on the pulse strength, and thus the dredge-up efficiency, as well as the intershell abundance and the temperature for the ^{22}Ne s-process. Finally, this investigation will prepare us to eventually study the He-shell flash with H-ingestion that occurs in about 1/4 of the central stars of planetary nebulae leading to the important class of

born-again AGB stars, as well as possibly in first, ultra-metal poor AGB stars.

Slide 5 (Setup, code, initial conditions)

We have performed … (walk down the itemized list)

The top figure shows the pressure evolution of the selected (15th) thermal pulse convection zone (grey area) as well as the He-luminosity evolution (right scale) according to the 1D stellar evolution computation. As a template for our hydro simulations we have picked the model just before the peak luminosity is reached. In this way we have the benefit of a large driving energy, but still a moderate range of pressure scale heights to include. The location of the hydrodynamic simulation is indicated with a red vertical line in the figure. The stratification comprises approximately 11 pressure scale heights, half of which represent the convectively unstable region. This gives enough simulation space both above and below the convection zone to avoid artifacts in the convection boundary simulation from simulation box boundary effects.

The bottom figure shows the vertical entropy profile of the initial setup. The entropy plateau representing the convection zone is clearly identifiable.

Slide 6 (Flow pattern)

Here we see a snapshot of the 1200x400 2D run. The color brightness represents pressure fluctuations; that is the pressure minus the horizontally averaged pressure. Over plotted are pseudo-streamlines to better visualize the flow pattern. In this simulation we increased the heating rate by a factor 30 over the realistic heating rate. Performing a grid of 2D simulations in resolution and energy driving was part of our

strategy to identify possible numerical artifacts and study the relative importance of stratification vs. heating rate.

The convective boundaries are well defined, sharp and clearly visible in this snapshot. The convective flow is dominated by 3 – 4 large systems, which vertically span the entire unstable layer, and are centered in the lower half of the unstable region. In the stable layers above and below the convection zone oscillations due to internal gravity waves can be seen.

Slide 7 (High-resolution 2D run)

This snapshot shows the entropy fluctuations of an even higher resolved 2400x800 2D simulation. In this case the same heating rate as in the stellar evolution model was applied. The same features as before can be identified. Although the resolution is higher the total number of large convective systems has not changed. We have observed this to be true for a large range of grid sizes, down to 300x100. The gravity wave oscillations in the top and bottom stable layers are even better visible. Note that this snapshot was taken at 4000s simulated time. The turnover time is approximately 600s. These simulations have been run out for many convective turnovers, for lower resolutions up to 20000s. These snapshots therefore represent convective steady state.

Slide 8 (Movie 2D)

Here we show a movie of entropy fluctuation for the 2D 1200x400 run with the realistic heating rate. It is interesting to note that the g-modes in the stable layer above the convection zone are already starting to get excited even before the convective motions have reached the top boundary of the unstable layer. The dynamic properties of both the unstable and the stable layers become now much more clear. In contrast

to shallow surface convection, for example in A-type stars, coherent convective systems do not cross the convective boundaries in a fashion visible in this representation. This is not surprising, because the relative stability of convective boundaries in the stellar interior is much larger than in stellar near-surface convection.

Slide 9 (3D horizontal slices entropy)

These panels show the entropy fluctuation in horizontal slices from our highest resolution 3D run. The snapshot is taken at 1665s, which again represents fully developed convection in steady state, after several convective turn overs. This sequence has been run out to 3000s. The panel represent locations in the stable layer below the convection zone (top, left), in the unstable layer (with red over- / underlines) and above the convection zone (lower right). The horizontal scales are a sensitive function of the depth. At the top and at the bottom of the convection zone large horizontal scales dominate, whereas in the middle (panel 3.33Mm) structures seem broken up and the flows seem more turbulent.

In the He-shell flash convection zone convection originates through heating at the bottom, contrary to surface or envelope convection that is driven by cooling from the surface. It is interesting to note that here we see at the bottom of the convection zone (panel 1.79Mm) similar granule-like structures as at the surface of solar-like convection.

Even outside the convection zone dynamic fluid motions exist, and their pattern again depend on the distance to the convective boundary. Panel 1.51Mm shows a very granular appearance with a lot of detail on small scales, whereas both the panels above and below show fluctuations on larger scales. The panels most distant from the convection zone, both above

and below, show a rather diffuse pattern of large-scale fluctuations.

Slide 10 (3D horizontal slices vertical velocity)

We have seen in the movie and the 2D snapshots, that the coherent convective systems do not cross the convective boundary on a scale that is any significant fraction, say of the horizontal scale. So one may conclude that there is no overshooting. This may be true, which does however not mean that there is no oscillation exitation and mixing across the boundary. Looking at the vertical velocity reveals how motions and oscillations in the the stable and unstable layer do in fact correlate, and therefore communicate. I have indicated some of these correlations in the next …

Slide 11 (3D horizontal slices vertical velocity with guidance for the eye)

It is not at all surprising that certain features in one slice have corresponding features neighboring slices above and below inside the convection zone, even if the dominating scales are different in different layers of the convection zone. We have already seen in the 2D snapshots and the movie that co-moving convective system traverse vertically the entire convection zone. However, what is maybe surprising is that the vertical velocity images also show that correspondence exists between the boundary planes just inside the convection zone and the neighboring planes several hundred km out in the stable layer. Thus, while convective systems do not cross the convective boundaries they do imprint their signature on the oscillation properties of the stable layers.

Slide 12 (k-ω diagram)

This correspondence between different layers, including nearby convective and non-convective layers, can be quantitatively studied in this figure that shows k-ω diagrams of several vertical planes. As before the panels corresponding to planes in the convectively unstable layer have a red over- or underline. In these diagrams the signature of convective motions shows up as an unordered blob in the lower, left part of the diagram. This is indicated here …

Slide 13 (k-ω diagram with markings)

with a green ellipse. In these diagrams the color darkness corresponds to the power in an oscillation with a given wave length and frequency. Within the convection zone the power is – not surprisingly – in the convective systems. However, as we can see from the panels representing the stable layers, these contain significant power in the convective motions as well. This is another sign of the correspondence discussed in the previous slides. Note that in the stable layers there is also the characteristic signature of gravity waves (encircled in light blue) and p-modes (in the far left columns of the panels).

We conclude at this point that our simulations show that convection does influence the fluid flows in the neighboring stable layers, both through exciting g-mode oscillations as well as enforcing motions with convective wavelengths and frequencies. We now need to look at how these correspondences between fluid flows on both sides of the convective boundary translate into actual mixing.

Slide 14 (Mixing for He-shell flash convection)

Bernd Freytag using a tracer particle technique to determine a diffusion coefficient at different horizontal positions, in particular across the convective boundaries has done this. The result of this approach (full details will be given in Freytag etal. 2006, in prep) is shown in the left figure for a 2D simulation with moderate resolution (600x200). Green circles and red crosses are diffusion coefficients using spread evolutions of entropy and vertical coordinate respectively. The first approach is more suitable to the stable layer; the second was chosen in the convection zone. In the transition layer both approaches give the same result. The solid black line is the merged, final result. The fall-off of the diffusion coefficient has then been fitted with an exponential, using the formalism employed in the AGB stellar evolution calculations by Herwig etal. 1997 and following papers. We find that at the bottom of the convection zone the convection induced mixing across the convective boundary can be described by a succession of two exponential decay laws. The first starts already somewhat inside the convection zone, and has an e-folding distance of $f_{bot,1}=0.01$, while just outside the convection zone when D has fallen to $\sim 10^5 cm^2/s$ the decay of mixing efficiency flattens and can be represented by $f_{bot,2}=0.14$. A similar procedure has been performed at the top boundary were our initial analysis gives a single exponential decay with $f_{top}=0.10$.

The two figures on the right show how the f-values depend on resolution and heating rate, as well as on 2D vs 3D effects. Overall we feel confident that our f-values are not off by very much. We will further investigate this issue.

This work represents our first attempt to extract convection induced mixing across the boundaries of He-shell flash convection from hydrodynamic simulations. Initial test stellar evolution calculations over a couple of thermal pulses implementing these hydrodynamic convective mixing results

indicate that we recover the increased O and C intershell abundance that we found in earlier calculations using the f-overshoot for this convection zone. First results indicate that we are obtaining C and O abundances that are consistent with observations of H-deficient PG1159 and [WC]-CSPN stars (see Werner & Herwig, 2006, PASP review for details).

We now need to spend a few more minutes to briefly look at two other non-convective mixing mechanisms.

Slide 15 (s-process in rotating AGB stars)

First, studies of rotation and its role on mixing for the s-process have shown that even if we can somehow form a ^{13}C-pocket, rotationally induced mixing during the interpulse phase poisons the ^{13}C-pocket with ^{14}N. In the figure shown here on the left green shows – after an assumed ^{13}C-pocket formation through a partial mixing process (see next slide)- the neutron exposure evolution during the interpulse phase without rotationally induced mixing, red shows in comparison the effect of rotation. A small neutron exposure as in the red case can not reproduce the s-process observables. The two panels on the right show the difference of the abundance profiles in the two cases, and that in the case with rotation the ^{14}N abundance is exceeding the ^{13}C abundance, thereby severely limiting the efficiency of the s-process through the highly efficient ^{14}N(n,p) poison reaction. This means that either the rotating models predict too much mixing, or that additional physics is missing. Magnetic fields could add angular momentum transport and reduce angular velocity gradients that cause shear mixing. However, there is another possibility that Corinne Charbonnel has recently pointed out, and that I find very promising, in particular in light of what we see in our hydrodynamic simulations. Internal gravity waves could have a similar desired effect. We see them plentiful in the hydro simulations, and their effect on mixing in AGB stars has not been studied in sufficient detail yet.

Slide 16 (Mixing for the ^{13}C pocket)

The only study of gravity waves in AGB stars I know of is that by Denissenkov & Tout (2002) who show that mixing induced by these waves may provide the conditions needed for the formation of a ^{13}C-pocket – see top figure on the right. Rotationally induced mixing (left figure) seems to produce a pocket that is not massive enough, while exponentially decaying convective extra-mixing or overshooting (bottom right) could do the trick as well. However, at this point the f-parameter can be freely adjusted, and due to the work of Lugaro etal. (2003) we know that in order to produce a large enough pocket to reproduce observables the f-parameter would have to be f~0.13. As I pointed out in the beginning of this talk, we can investigate the exact nature and quantity of this mixing using hydrodynamic simulations in the not too distant future. From our experience with He-shell flash convection simulations my guess is that it will be mixing as a result of the non-linear interaction of gravity waves with a small amount of overshooting.

In any case, at this point I would like to make a final remark that brings us back to the hydro-simulation results presented earlier. Any of the three mechanisms for partial mixing shown on this slide have inevitably one thing in common. They lead to a steady transition of the H/^{12}C ratio from high at the bottom of the convective envelope to zero in the ^{12}C-rich core. While this sounds trivial it has an important consequence:

Slide 17 (Intershell C vs max neutron exposure)

The maximum ^{13}C abundance in the pocket, and therefore the maximum neutron exposure is determined most importantly by the ^{12}C abundance in the intershell of the preceding thermal

pulse. This has been shown by Lugaro etal. (2003), and the relationship between intershell ^{12}C and maximum neutron exposure as derived from a series of numerical experiments is shown in this figure. The filled symbol represents the neutron exposure obtained with the standard intershell ^{12}C abundance of $X_C \sim 0.24$. This neutron exposure can approximately be identified with the "standard" ^{13}C-pocket in the parametric models of Gallino, Busso and collaborators. However, their studies over the years have also shown that a number of observations require a higher neutron exposure to correctly reproduce the observed hs/ls indices. The hydrodynamic convective extra-mixing observed at the bottom of the thermal pulse convective shell in the simulations presented earlier in this talk have the effect of increasing the intershell ^{12}C abundance. In conjunction with a realistic mixing process for the formation of the ^{13}C-pocket this could be an important ingredient to reproduce observations indicating the highest neutron exposures. Weak rotationally induced mixing, moderated by magnetic fields and/or gravity waves may then quite naturally explain the observed spread in neutron exposures – through mild ^{14}N poisoning of the ^{13}C-pocket. Clearly – much more research in this area is required.

Slide 18 (Conclusions)

- Full hydrodynamic simulations of convection in AGB stars, both in the envelope and in the intershell are now becoming feasible, and offer a new exciting tool to study mixing.
- Our simulations of He-shell flash convection allow a first quantitative glimpse at mixing at and across the convective boundary.
- The simulations emphasize the need to study the role of gravity waves in much greater detail.
- Rotating models do currently not reproduce observables.